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Study of process of avalanche switching of silicon thyristors without bias voltage

O E Perminova¹ and S N Tsyrnov^{1,2}

¹Ural Federal University, 19 Mira Street, Yekaterinburg, 620002, Russia

²Institute of Electrophysics, 106 Amundsen Street, Yekaterinburg, 620016, Russia

E-mail: serg@iep.uran.ru

Abstract. Operation of the high-power thyristor without bias voltage switching in the impact-ionization mode was studied by numerical simulation methods. In calculations, the rate of voltage build-up on the dV/dt structure varied from 0.5 to 10 kV/ns, the temperature of the T structure was from 25 to 200 °C. It is shown that the increase in temperature affects the process of switching thyristors both due to an increase in the rate of thermal generation of carriers, and due to a decrease in the intensity of impact ionization processes. During switching processes of impact ionization occur at the same time in two regions of n -base: in the part of a base filled with the majority carriers and in the space charge region (SCR) near the n - p junction. At $T > 180$ °C, owing to increase in concentration of thermo-generated carriers in the base, ionization processes occur only in SCR. It leads to increase in duration of switching process and increase in residual voltage. However, despite it if $dV/dt > 9$ kV/ns, the effect of fast switching of the thyristor exists up to 200 °C.

1. Introduction

In the last decade semiconductor switches on the basis of dynistor structures with a time of transition into a conducting state for less than 1 ns were developed [1, 2]. Such switches – deep-level dynistors (DLDs) – are able to switch a current of several kiloamperes at a current rise rate of up to 200 kA/μs. A DLD is switched into a conducting state upon application of an overvoltage pulse with a rise rate more than 1 kV/ns. This allows the electric field in the plane of the collector junction of the dynistor to be increased to values of 300-350 kV/cm, at which an intense ionization of deep levels in silicon is initiated. The injection of electrons from these centers into the structure region with a high field initiates an impact-ionization wave, which passes through the structure of a device and uniformly fills its entire area with dense electron-hole plasma. The wave motion velocity is considerably higher than the saturated velocity of carriers in silicon, the structure of a device with a typical wafer thickness of several hundred microns and a carrier transit time of a few nanoseconds is filled with plasma with a time of several hundred picoseconds [3-5].

Recently it was shown that this principle of current switching can also be realized in conventional industrial thyristors. When thyristors are triggered in the impact-ionization wave mode, the device with switch to the conductive state within 200-400 ps, the rate of current rise will exceed 100 kA/μs, and the amplitude of the current can reach the value of 200 kA [6-9]. Compared with the traditional mechanism for triggering the thyristor by a current pulse through the gate electrode the dl/dt value was increased about 250 times. It was shown that the voltage rise rate at the triggering stage was the main



factor affected on the time of switching the thyristor from the blocking state to the conducting state [10, 11]. To explain a number of experimental data and to obtain agreement between the experimental and calculated oscillograms at the switching stage is possible only on the assumption that the front extends over a part of the area of the structure called an active area [8, 11].

However, practically there are no data on the influence of the temperature of the semiconductor structure on the processes of initiation and propagation of ultrafast fast ionization fronts. It is pointed out to the fact that such switching process is observed in the range from the temperature of liquid nitrogen and completely dropped out with the temperature rise of more than 90 °C [4].

The aim of this study is to theoretical research the influence of the joint effect of temperature and voltage rise rate in the thyristors without bias voltage on the process of the triggering to the conductive state. The research is carried out with a change in the value of dV/dt from 0.5 to 10 kV/ns and the temperature of the structure T from 25 to 200 °C. We will notice that switching of a thyristor in the mode with bias voltage is impossible at a temperature more than 180 °C because of its spontaneous inclusion. Switching of the thyristor in the mode without bias voltage is free from this restriction.

2. Model

The model description of numerical simulations for the processes of shock-ionization switching of thyristor is detailed in [10]. The calculation is carried out using a one-dimensional physical and mathematical model composing of the joint solution of the Kirchhoff equations describing the operation of the electrical circuit with a thyristor and the equations of the dynamics of electrons and holes in the thyristor structure. The calculation uses the real distribution profile of doping impurities in the thyristor structure, and the parameters of the design electric circuit correspond to the experimental scheme. To calculate the dynamics of electrons and holes in the thyristor structure, we use the basic semiconductor equations consisting of the continuity equations for electrons and holes, the Poisson equation for the electric field, and the heat flow equation for temperature. The dependence of the mobility of electrons and holes on the electric field, temperature, electron-hole scattering, and scattering on ionized impurities is taken into account. The calculation takes into account the generation-recombination processes according to the Reed-Shockley-Hall model, as well as the space velocity of the avalanche and tunnel generation of electron-hole pairs, including carrier generation processes during ionization of deep levels. The present model takes into account the dependence of avalanche multiplication factors on the electric field and temperature [12].

In compliance with the results received in [10, 11], the model includes the following provisions: (a) to avoid triggering the front due to the avalanche propagation of unphysically small concentrations of free carriers [5], impact ionization processes are activated at the time when the carrier concentration at any point of the structure reaches the value $n_0 = 0.5 \cdot 10^9 \text{ cm}^{-3}$, (b) the concentration of deep M-type levels (0.54 eV) is $N_{PI} = 10^{12} \text{ cm}^{-3}$, (c) the dependence of the active area of the structure through which the thyristor switches to the conductive state on the rate of voltage dV/dt is taken into account [11].

The thyristor has the structure of $p^+-p-n-p-n^+$ type 520 μm in thickness and is made by diffusion technology of n -type Silicon with specific resistance $\rho = 80\text{--}85 \text{ } \Omega \cdot \text{cm}$. Alloying impurities are distributed as follows: the p^+ -area is formed by boron diffusion (10^{18} cm^{-3} , 50 μm), the p -region – by diffusion of aluminum ($2 \cdot 10^{16} \text{ cm}^{-3}$, 85 μm), n^+ -region by phosphorus diffusion (10^{19} cm^{-3} , 20 μm). The numbers in parentheses indicate the boundary concentration and the depth of the impurity.

The thyristor switch contained tablet thyristor with DC operating voltage of 2.4 kV, and diameter of silicon wafer of 32 mm. The magnitude of the initial bias voltage V_0 was 0 kV.

3. Simulation results

3.1 Simulation results for thyristors without bias voltage

The calculated oscillograms of the voltage across the thyristor and their comparison with the experimental ones at value of $dV/dt = 9.2 \text{ kV/ns}$ and two temperatures $T = 175 \text{ } ^\circ\text{C}$ and $200 \text{ } ^\circ\text{C}$ are given in figure 1. With growth of temperature from 170 to 200 °C concentration of carriers in n -base

increase twice (figures 2b-2b') that causes decrease twice in resistance of the thyristor and voltage rise rates on it (figure 1). At $T=170^\circ\text{C}$ processes of impact ionization occur at the same time in two regions of n -base: in the part of a base filled with the majority carriers and in the SCR near the n - p junction (figure 2b). It is important to note that while in SCR the impact-ionization front is formed, in the part of a base filled with the majority carriers, processes of ionization occur in all points of this area at the same time (figures 2b-d).

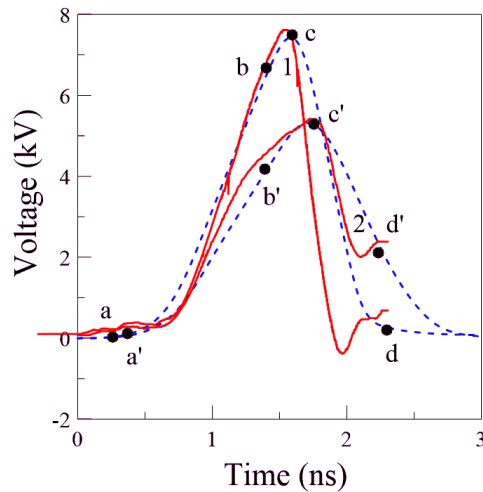


Figure 1. Experimental (solid curves) and calculated (dashed curves) time dependences of the voltage across the thyristor at $dV/dt = 9.2 \text{ kV/ns}$ and different temperatures: $T=175^\circ\text{C}$ (curves 1) and 200°C (curves 2).

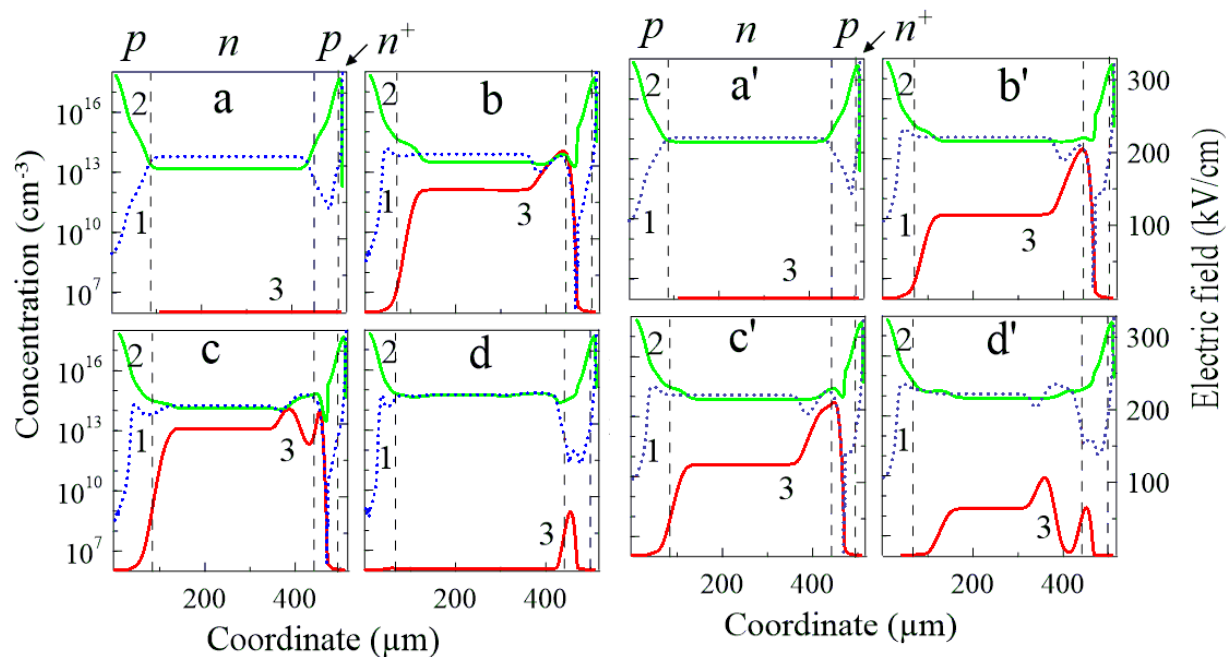


Figure 2. Distributions of the electron concentration (curves 1), hole concentration (curves 2), and electric field (curves 3) across the thyristor structure at time moments a–d in figure 1 for $T=175^\circ\text{C}$ and a'–d' for $T=200^\circ\text{C}$.

Contribution of the SCR to total voltage on the thyristor doesn't exceed 30%. During switching process density of carriers in base increases by 2 orders and reaches the value of $\sim 10^{15} \text{ cm}^{-3}$ (figure 2d). At $T=200^\circ\text{C}$, owing to increase in concentration of thermo-generated carriers, ionization

processes occur only in SCR (figure 2b'). It leads to increase in duration of switching process and increase in residual voltage, which is created in a base out of SCR (figure 2d').

3.2 Comparison of simulation results for thyristors with bias voltage and without it

The calculated oscillograms of the voltage across the thyristor and their comparison with the experimental ones at $dV/dt = 9.2$ kV/ns and $T = 175$ °C for thyristors with bias voltage and without it are given in figure 3. In the thyristor with bias voltage the impact ionization processes occur only in SCR where impact-ionization front is formed (figure 4b'), which passes through the n -base and uniformly fills its area with electron-hole plasma with a density of $\sim 5 \cdot 10^{15}$ cm $^{-3}$ (figure 4d').

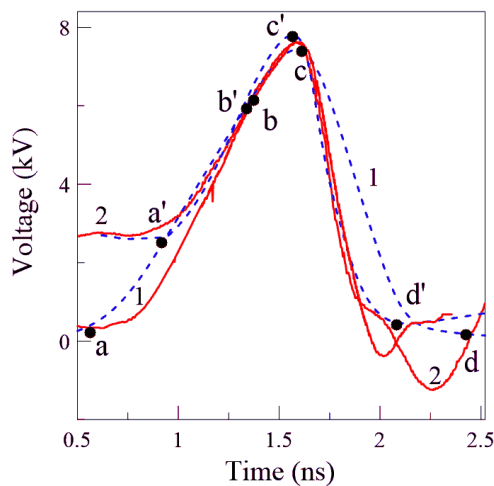


Figure 3. Experimental (solid curves) and calculated (dashed curves) time dependences of the voltage across the thyristor at $dV/dt = 9.2$ kV/ns and $T = 175$ °C for different modes: without bias voltage (curves 1) and with bias voltage (curves 2).

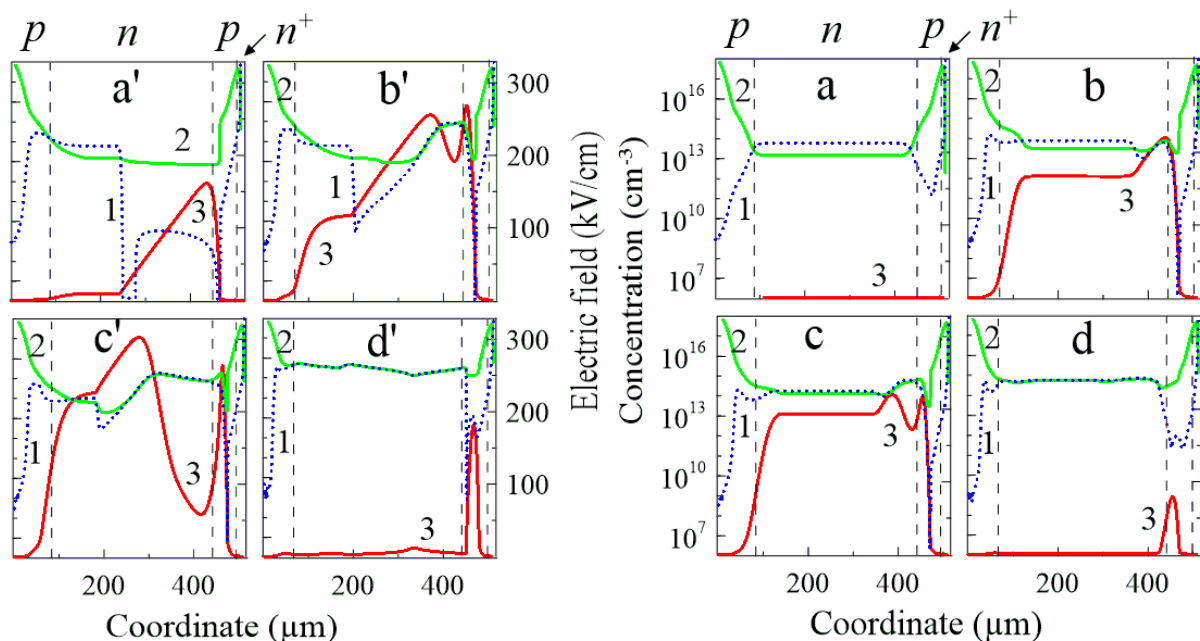


Figure 4. Distributions of the electron concentration (curves 1), hole concentration (curves 2), and electric field (curves 3) across the thyristor structure at time moments a-d in figure 3 for the mode without bias voltage and a'-d' for the mode with bias voltage.

During propagation of an impact-ionization front across base of the thyristor of value of amplitude of an electric field, speed of filling of a base with plasma and concentration of plasma in it reach higher values in the mode with bias voltage (figures 4b'-4d') than in the mode without it (figures 4b-4d). It leads to the fact that after completion of process of switching residual voltage in the mode without bias voltage (figure 4d) is more than in the mode with bias voltage (figure 4d'). Despite all this the switching voltage and switching time in these modes are close to each other (figure 3).

4. Conclusion

The joint effect of temperature and the voltage rise rate in the silicon thyristor on the process of its switching studied by numerical simulation methods. In calculations, the rate of voltage build-up on the dV/dt structure varied from 0.5 to 10 kV/ns, the temperature of the T structure was from 25 to 200 °C.

It is shown that the increase in temperature affects the process of switching thyristors both due to an increase in the rate of thermal generation of carriers, and due to a decrease in the intensity of impact ionization processes. Let us single out the following main results.

First, when switching the thyristor without bias voltage processes of impact ionization occur at the same time in two regions of n -base: in the part of a base filled with the majority carriers and in the space charge region (SCR) near the n - p junction. It is important to note that while in SCR the impact-ionization front is formed, in the part of a base filled with the majority carriers, processes of ionization occur in each point of area. During switching process, the contribution of SCR is small both on the rate of voltage reduction, and on voltage amplitude, not exceeding 30% of total thyristor voltage.

Secondly, at $T > 180$ °C, owing to increase in concentration of thermo-generated carriers in the thyristor, ionization processes occur only in SCR. It leads to increase in duration of switching process and increase in residual voltage, which is created in a n -base out of SCR. However, despite it if dV/dt exceeds value of ~9 kV/ns, the effect of fast switching of the thyristor exists up to 200 °C.

Thirdly, in the thyristor with bias voltage the impact ionization processes occur only in SCR where impact-ionization front is formed, which passes through the structure of a device and uniformly fills its area with dense electron-hole plasma. During propagation of an impact-ionization front across base of the thyristor of value of amplitude of an electric field, speed of filling of a base with plasma and concentration of plasma in it reach higher values in the mode with bias voltage than in the mode without bias voltage. It is necessary to emphasize that such distinction exists at an identical voltage is also a consequence of different geometry of distribution of an electric field in a thyristor base: in the mode with bias voltage the field is concentrated in SCR, and in the mode without bias voltage the electric field is distributed along n -base. We will note that despite qualitative difference of the processes happening in base of the thyristor at a stage of switching, characteristics of process of switching appear in the modes with bias voltage and without it are close to each other.

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